南大洋で進行する海洋酸性化

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Ocean acidification progressing in the Southern Ocean

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The Southern Ocean is considered to have a significant impact on global air-to-sea CO_2 fluxes because of the large cold surface area, regional wind velocity and high export production. The long-term increase in the partial pressure of CO_2 in surface waters ($p\mathrm{CO_2}^{sea}$) was found in the extensive region north of the seasonal sea ice zone, i.e., from the subtropical to polar zone (Inoue and Ishii, 2005). The uptake of anthropogenic carbon by the ocean has given rise to changes in chemical equilibrium in the surface ocean CO_2 system, resulting in a reduction of seawater pH, i.e., the ocean acidification. Model simulations have indicated that anthropogenic ocean acidification might impact calcifying organisms at high latitudes, particularly in the Southern Ocean, within the next few decades (Orr et al., 2005).

We estimated long-term trends of surface ocean acidification in the western Pacific sector of the Southern Ocean (Fig. 1). Estimates were based on the observational data of surface carbonate parameters from seven cruises in Austral summer for 1969 to 2003 (Table 1). The trends are compared with the recent observation data in the Indian sector in 2009–2010.

The pH values were calculated from sea surface temperature (SST), salinity, $p\mathrm{CO_2}^{sea}$ and dissolved inorganic carbon (or total alkalinity) by using the methods of Dickson et al. (2007). For cruises with only one carbonate parameter, total alkalinity (TA) was estimated from SST and SSS using the empirical equation by Lee et al. (2006) and used for the pH calculation.

Table 1. Cruises and parameters of surface observations

Cruise	Year/Month	Observed parameters
KH68-4	1969/Jan.	SST, SSS, $p\mathrm{CO_2}^{sea}$, TA
KH83-4	1983/Dec., 1984/Jan.	SST, SSS, $p\mathrm{CO_2}^{sea}$
JARE34	1992/Dec., 1993/Feb.	SST, SSS, DIC
KH94-4	1994/Dec., 1995/Jan.	SST, SSS, $p\mathrm{CO_2}^{sea}$, DIC
KH01-3	2002/Jan.	SST, SSS, $p\mathrm{CO_2}^{sea}$, DIC
JARE43	2002/Feb.	SST, SSS, $p\mathrm{CO_2}^{sea}$, DIC
JARE44	2003/Mar.	SST, SSS, DIC
KH09-5	2009/Dec., 2010/Jan.	SST, SSS, $p\mathrm{CO_2}^{sea}$, DIC

SST, sea surface temperature; SSS, sea surface salinity; $p\mathrm{CO_2}^{sea}$, oceanic CO_2 partial pressure; DIC, dissolved inorganic carbon; TA, total alkalinity

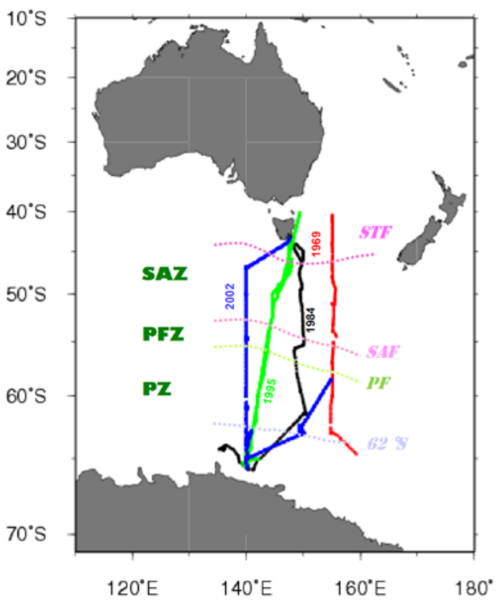

Fig. 1. Major cruise tracks in the western Pacific sector. The data were divided into four zones: the zone north of the Subtropical Front (STF), where the partial pressure of CO_2 in surface waters ($p\mathrm{CO_2}^{sea}$) was at a minimum; the Sub-Antarctic Zone (SAZ) between STF and the Sub-Antarctic Front (SAF); the Polar Frontal Zone (PFZ) between SAF and the Polar Front (PF); the Polar Zone (PZ) between PF and 62°S.

The time-series data for pCO_2^{sea} showed substantial increasing trends in the extensive region from the subtropical to polar zone. The increasing rates of pCO_2^{sea} were lower than those in the atmosphere (pCO_2^{air}) in the zones north of the PF (0.8 ± 0.2 to 1.2 ± 0.2 µatm yr^{-1}) and higher in the PZ (1.7 ± 0.2 µatm yr^{-1}). On the other hand, SST, SSS and TA normalized to a salinity of 34, n-TA, had no trend over the zones studied.

The computed pH time series exhibited significant decreasing trends in the extensive region from subtropical to polar zones. The mean rates of pH decrease for 35 years were 0.0010 to 0.0013 yr^{-1} in the zones north of the PF and relatively large in the PZ (0.0020 yr^{-1}), corresponding to those of pCO_2^{sea} and salinity-normalized DIC, n-DIC. The contribution of SST trends to the decreasing pH trends was small in all zones. The pH estimated from the new observation data from the Indian sector in January 2010 was consistent with 35-year trends in the western Pacific sector.

The pH decreasing rates in the zones north of the PF were attributed primarily to the long-term n-DIC increase derived from the accumulation of anthropogenic CO_2 from the atmosphere, based on the calculation using observed pCO_2^{sw} increase rates and buffer factors in these regions. A larger decreasing rate of pH in the PZ suggests the contribution of alternative process in this region. One of its explanation might be the additional effects of enhanced upwelling caused by the recently intensified wind stress, as reported by Le Quéré et al. (2007), superimposed to the accumulation of anthropogenic CO_2.

On the basis of the observation results, the tentative evaluation of thermodynamic changes in the upper carbonate system in the PZ under the future CO_2 emission scenario IS92a (IPCC, 2007) suggests that the surface pH could decrease by ca. 0.2 in the next 75 years and the calculated index Ω for aragonite saturation projects that the PZ would be undersaturated with respect to aragonite in summer after 80 years later. The simulation from the wintertime observations projected a more rapid onset of aragonite undersaturation in winter.

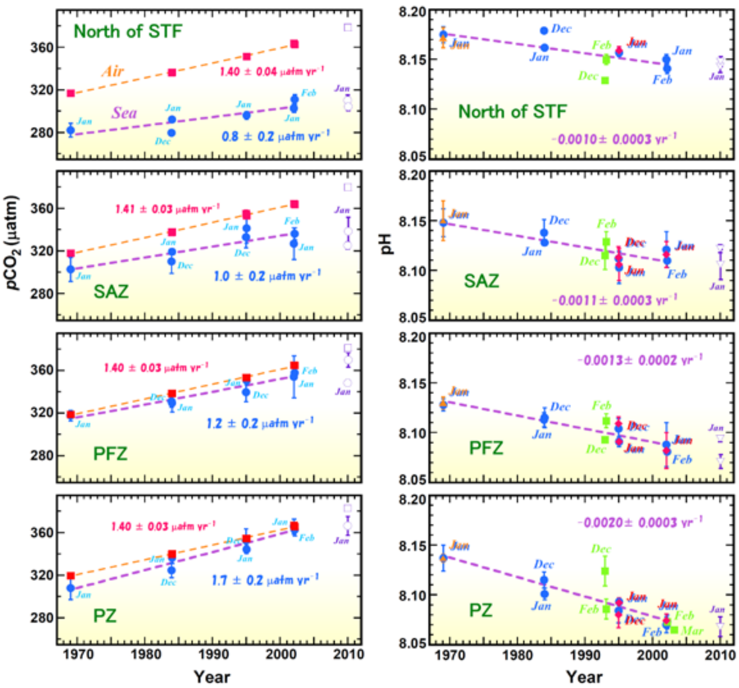

Fig. 2. Time series of observed pCO_2^{sea} and estimated pH averaged during the respective periods (legs of cruises). Error bars represent 1σ values for the value range in the zone. Blue circles and green squares are based on one parameter observation: blue, pCO_2^{sea}; green, DIC. Red diamonds and orange triangle are based on two-parameter observation: red, DIC and pCO_2^{sea}; orange, TA and pCO_2^{sea}. The trends are for the period of 1969–2003 and the data from the Indian sector in 2010 (violet open triangles) were not included.

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